

**FINAL REPORT FOR NASA GRANT NO. NAGW-4723
(ALSO REFERENCED AS NAG5-3341)**

TITLE: DEVELOPMENT OF A TELE-MICRO-ROBOT FOR TELEMANIPULATION OF A MICROSCOPIC ENVIRONMENT
INSTITUTION: VANDERBILT UNIVERSITY
PRINCIPAL INVESTIGATOR: MICHAEL GOLDFARB
PERIOD COVERED BY STATUS REPORT: August 1995 through June 1998

GENERAL RESEARCH OBJECTIVE

The objective of the proposed work was to design and develop the mechanical equivalent of a stereomicroscope in order to eliminate the mismatch that currently exists between one's ability to observe a microscopic environment and one's ability to manipulate it.

SIGNIFICANT RESEARCH ISSUES

The presence of backlash and Coulomb friction in a manipulator severely impair the ability to implement effective control of any endpoint force-based quantity. Due to the physics of scaling, these highly nonlinear effects become increasingly significant with decreasing scale. Consequently, an effective micromanipulator that will enable dexterous manipulation in a microscopic environment cannot simply be fabricated as a scaled-down version of a conventional-scale manipulator. Instead, development of a successful microrobot capable of accurate and competent force-controlled micromanipulation will necessitate elimination or intelligent minimization of surface force behavior.

DESCRIPTION OF PROJECTS

Completed Work

Modeling and Control of Piezoelectric Stack Actuators for Control of Micromanipulation (Goldfarb and Celanovic)

A successful microrobot requires actuation which should minimize surface force influence, have a bandwidth at minimum sufficient for human-controlled manipulation, and provide a range of motion and endpoint forces suitable for an optically-based imaging system. The investigator and student considered and tested several actuators with which to actuate a microrobot, including piezoelectric ceramic, shape memory alloy, electromagnetic devices, and magnetostrictive and electrostrictive materials. These investigations indicate that piezoelectric ceramic, coupled with an intelligently-designed transmission, is well-suited to the desired actuation performance. The use of PZT stack actuators for accurate and stable control of manipulator position and/or force is greatly facilitated by model-based control system analysis and design. The purpose of this project was to formulate a model of piezoelectric ceramic to provide general insight into PZT behavior as well as a specific causal mathematical representation for purposes of model-based control system analysis and design. The work resulted in the publication of two journal papers, one entitled *Modeling Piezoelectric Stack Actuators for Control of Micromanipulation* and one entitled *A Lumped-Parameter Electromechanical Model for Describing the Nonlinear Behavior of Piezoelectric Actuators*.

Microgripper Design for Force-Reflective Telemanipulation of a Microscopic Environment (Goldfarb and Celanovic)

The presence of backlash and Coulomb friction in a manipulator severely impair the ability to implement effective control of any endpoint force-based quantity. Since scaling exacerbates these highly nonlinear effects, effective implementation of force-based control on a micromanipulator requires intelligent minimization of backlash and Coulomb friction, an approach which the authors refer to as minimum surface effect design. In this project, the investigator and student designed, fabricated, and evaluated a force-reflective teleoperative macro-microgripper pair. This telerobotic system served primarily as a one degree-of-freedom investigation of a flexure-based microrobot design. The gripper design, which is pictured in Figure 1, verified the minimum surface effect hypothesis, and the results of this project serve as the foundation for present work focusing on the design of a three degree-of-freedom micromanipulator. Please refer to the enclosed manuscript, entitled *A Flexure-Based Gripper for Small-Scale Manipulation* for a more detailed description of this work.

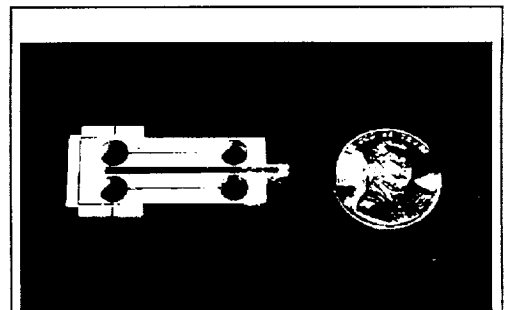


Figure 1. Force-Reflective Microgripper.

Design of an Open-Section Flexure (Goldfarb and Speich)

Design of the flexure-based microgripper indicated that flexure-based design offers significant performance advantages with respect to manipulator control, but when implemented with conventional flexure hinges, the design also presents several inadequacies. These include a severely restricted range of motion, poor kinematic properties under spatial loading, and large joint stiffness. Such properties indicate a clear need for an alternative flexure design that offers a significant range of motion, good spatial kinematic behavior, low joint stiffness, and operation devoid of backlash and Coulomb friction. The investigator and student have developed an open-section flexure joint that offers near ideal flexure properties, as described in the attached paper. This joint is extremely well-suited for construction of a precision micromanipulator, and has been incorporated into the design of the three degree-of-freedom precision micromanipulator. Please refer to the enclosed manuscript, entitled *A Well-Behaved Revolute Joint for Compliant Mechanism Design* for a more detailed description of this work.

Design of a High Performance Zero Backlash Three Degree-of-Freedom Parallel Manipulator (Goldfarb and Perry)

A three degree-of-freedom manipulator provides the force-reflective interface between the human operator and the micromanipulator. The investigator and student have designed and fabricated the manipulator, which is pictured in Figure 2. The manipulator performance has been characterized (Goldfarb and Beale), and the investigator and students are presently utilizing the device to conduct control and haptic interface studies (Goldfarb, Kilchenman, Sirithanipat). Please refer to the enclosed manuscript, entitled *A Compliant-Mechanism-Based Three Degree-of-Freedom Manipulator for Small-Scale Manipulation* for a more detailed description of this work.

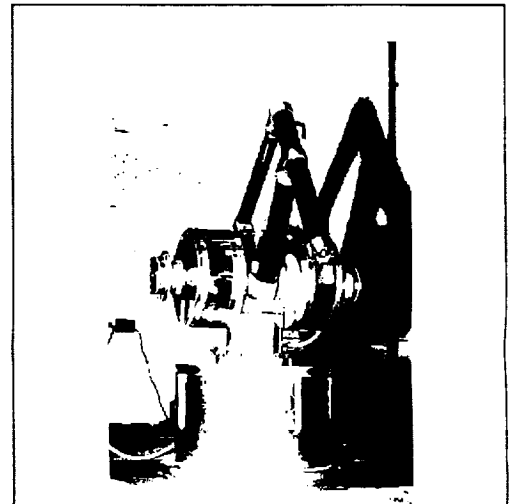


Figure 2. Precision Master Manipulator.

Force-Optimized PZT-Based Microactuator Package (Goldfarb and Lipsey)

Piezoelectric ceramic actuators are well-suited as actuators for micromanipulation, with the exception of two major inadequacies. First, they typically provide only 15 microns of displacement; second, the actuator force decreases linearly with increasing displacement. Useful micromanipulation under a microscope requires a range of motion of at least five millimeters cubed, which implies that the ceramic actuator requires a mechanical transmission of approximately 300 times, without any backlash or friction. Additionally, an ideal actuator should have roughly constant force capabilities across its range of motion. The investigator and student have developed an innovative actuator package that incorporates highly nonlinear behavior to favorably "distort" the output properties of the actuator to achieve a total output displacement of approximately one millimeter with approximately uniform output force characteristics. The investigator and student are presently testing this actuator package to evaluate and characterize its performance. Please refer to the enclosed manuscript, entitled *Design of a Minimum Surface-Effect Tendon-Based Microactuator for Micromanipulation* for a more detailed description of this work.

Design of a Three Degree-of-Freedom Micromanipulator (Goldfarb and Speich)

The development of the aforementioned flexural revolute joint makes possible the development of a high performance force-controlled three degree-of-freedom micromanipulator. The micromanipulator is designed for a workspace of approximately two centimeters in diameter, positioning resolution of a micron, for forces up to several hundred milliNewtons and a force resolution of approximately one part in a thousand. A two degree-of-freedom prototype, shown in Figure 3, is presently being characterized. Once tested, the third degree of freedom will be added. Once completed, the three degree-of-freedom micromanipulator will be one of the most unique and advanced compliant micromechanisms in existence.

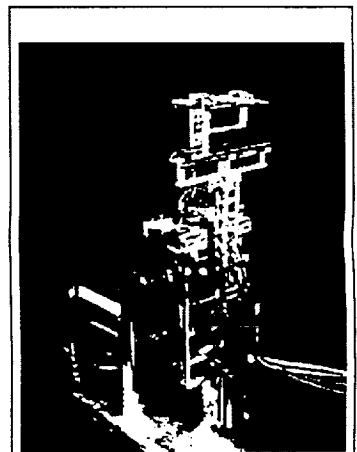


Figure 3. Two DOF Micromanipulator Prototype with Split-Tube Flexure Joints.

***Minimizing Distortion in Scaled Telemanipulation* (Goldfarb)**

The bilateral scaling of a general dynamic environment will introduce distortion of the intensive properties of the environment, such as the density, viscosity, and modulus of elasticity. A methodology was developed which incorporates dimensional analysis techniques to form the basis of a constrained optimization problem that enables a set of scaling gains that minimize the intensive distortion of the environment. This methodology is described in the paper entitled *Similarity and Invariance in Scaled Bilateral Telemanipulation*.

***Transparency and Stability in Bilateral Telemanipulation* (Goldfarb, Fite, and Speich)**

A related subject to the one previously described is the topic of transparency and stability in scaled teleoperation. Specifically, a bilateral teleoperation system should ideally preserve the "feel" of the environment with which the operator interacts, and further do this in a robustly stable manner. The latter is particularly important because the machine is in contact with a human. Previous work published in this area generally maintained that transparency and stability are competing objectives. A control architecture was developed for a two-channel bilateral control system that utilizes loop compensation to simultaneously enhance both stability and transparency. This work has not yet been published, but is the subject of a paper by Fite, Goldfarb, and Speich currently in review.

PUBLICATIONS RESULTING FROM THIS FUNDING

- Goldfarb, M. and Celanovic, N. A Lumped-Parameter Electromechanical Model for Describing the Nonlinear Behavior of Piezoelectric Actuators. *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 119, no. 3, pp. 478-485, 1997.
- Goldfarb, M. and Celanovic, N. Modeling Piezoelectric Stack Actuators for Control of Micromanipulation. *IEEE Control Systems Magazine*, vol. 17, no. 3, pp. 69-79, 1997.
- Goldfarb, M. and Celanovic, N. A Flexure-Based Gripper for Small-Scale Manipulation. *Robotica*, vol. 17, no. 2, pp. 181-188, 1999.
- Goldfarb, M. Similarity and Invariance in Scaled Bilateral Telemanipulation. *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 121, no. 1, pp. 79-87, 1999.
- Goldfarb, M. and Speich, J.E. A Well-Behaved Revolute Joint for Compliant Mechanism Design. *ASME Journal of Mechanical Design*, vol. 121, no. 3, pp. 424-429, 1999.
- Goldfarb, M. and Jones, L. D. On the Efficiency of Electric Power Generation with Piezoelectric Ceramic. *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 121, no. 3, pp. 566-571, 1999.
- Speich, J.E. and Goldfarb, M. A Compliant-Mechanism-Based Three Degree-of-Freedom Manipulator for Small-Scale Manipulation. *Robotica*, In press.
- Fite, K., Speich, J., and Goldfarb, M. Transparency and Stability in Two-Channel Bilateral Telemanipulation. Submitted to the *ASME Journal of Dynamic Systems, Measurement and Control*, August 1999.
- Goldfarb, M. and Celanovic, N. Behavioral Implications of Piezoelectric Stack Actuators for Control of Micromanipulation. In *Proceedings of the IEEE Conference on Robotics and Automation*, pp. 226-231, April 1996.
- Goldfarb, M. and Celanovic, N. Minimum Surface Effect Microgripper Design for Force-Reflective Telemanipulation of a Microscopic Environment. In *Proceedings of the ASME International Mechanical Engineering Conference and Exposition*, DSC-Vol. 58, pp. 477-482, November 1996.
- Goldfarb, M. and Speich, J. Design of a Minimum Surface-Effect Three Degree-of-Freedom Micromanipulator. In *Proceedings of the IEEE Conference on Robotics and Automation*, pp. 1466-1471, April 1997.
- Goldfarb, M. and Lipsey, J. Design of a Minimum Surface-Effect Tendon-Based Microactuator for Micromanipulation. In *Proceedings of the IEEE Conference on Robotics and Automation*, pp. 1460-1465, April 1997.
- Goldfarb, M. Dimensional Analysis and Selective Distortion in Scaled Bilateral Telemanipulation. In *Proceedings of the IEEE Conference on Robotics and Automation*, pp. 1609-1614, May 1998.
- Goldfarb, M. and Speich, J. Eliminating Non-Smooth Nonlinearities with Compliant Manipulator Design. In *Proceedings of the IEEE/ASME American Control Conference*, pp. 2118-2122, June 1998.
- Goldfarb, M. and Speich, J. Compliant Micromanipulator Design for Scaled Bilateral Telemanipulation of Small-Scale Environments. *ASME International Mechanical Engineering Conference and Exposition*, DSC-Vol. 64, pp. 213-218, November 1998.

STUDENT THESES DIRECTED TOWARD GRANT OBJECTIVES

Completed theses supported or partially supported by grant

- Celanovic, Nikola. *Macro-micro Gripper Pair for Force-reflective Microscopic Telemanipulation*. Master of Science Thesis, Department of Mechanical Engineering, Vanderbilt University, Nashville, TN, May 1996.
- Perry, Carl. *Design of a High Performance Zero Backlash Three Degree-of-Freedom Parallel Manipulator*. Master of Science Thesis, Department of Mechanical Engineering, Vanderbilt University, Nashville, TN, May 1997.

Theses supported or partially supported by grant

- Speich, John. *Minimum Surface Effect Design of a Three Degree-of-Freedom Micromanipulator*. Master of Science Thesis, Department of Mechanical Engineering, Vanderbilt University, Nashville, TN, December 1997.
- Lipsey, James. *Minimum Surface Effect Microactuator for Micromanipulation*. Master of Science Thesis, Department of Mechanical Engineering, Vanderbilt University, Nashville, TN, December 1997.

Theses directed toward grant objectives but supported by other means

- Siripanipet, Taweedej. *Selection of PD Control Gains for Nonlinear Servo Systems*. Master of Science Thesis, Department of Mechanical Engineering, Vanderbilt University, Nashville, TN, December 1996.
- Monopoli, Daniel J. *Development of a Three Degree-of-Freedom Load Cell for use in a Force Reflective Telemanipulator*. Bachelor of Science Thesis, Department of Mechanical Engineering, Vanderbilt University, Nashville, TN, May 1996.
- Lathrop, Ray. *Design of a Three Degree-of-Freedom Stylus for a Force-Reflective Master Manipulator*. Department of Mechanical Engineering, Vanderbilt University, Nashville, TN, May 1997.
- Beale, Jennifer. *Calibration of a Three Degree-of-Freedom Manipulator*. Department of Mechanical Engineering, Vanderbilt University, Nashville, TN, May 1997.
- Kilchenman, Marcia. *The Effect of Machine Performance on Haptic Fidelity*. Master of Science Thesis, Department of Mechanical Engineering, Vanderbilt University, Nashville, TN, May 1998.